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THESIS

OPTIMAL AIRCRAFT CARRIER DEPLOYMENT SCHEDULING

by

Craig T. Schauppner

March 1996

Thesis Advisor: Siriphong Lawphongpanich

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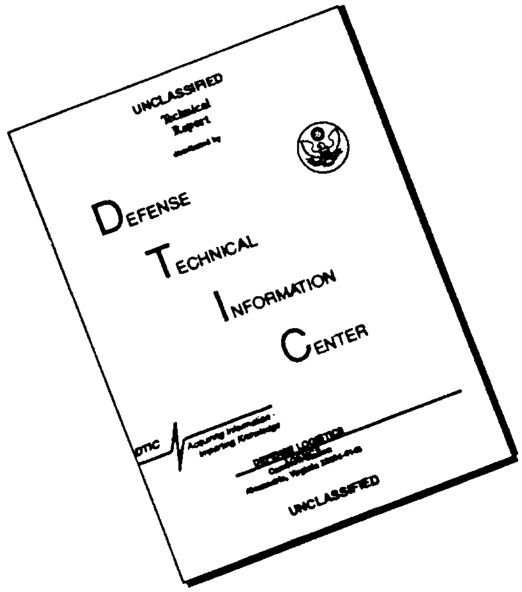

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The CINCPACFLT Operations Department maintains a five year deployment plan for the six carriers assigned to the Pacific Fleet. Currently, the deployment schedule is produced manually. A feasible five year plan typically takes the carrier scheduling officer one week to generate. This thesis presents an optimization based tool to assist in constructing deployment schedules that maximize the forward presence of Pacific Fleet carriers. The underlying optimization model is different from those in the literature. Instead of using a set covering approach, the problem is formulated as a shortest path problem with side constraints. This formulation allows the problem to be solved more rapidly, thus allowing more opportunities for sensitivity and trade-off analyses.

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OPTIMAL AIRCRAFT CARRIER DEPLOYMENT SCHEDULING

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power." To meet this mission, the Navy deploys aircraft carriers to forward positions throughout the world. A new nuclear powered aircraft carrier costs over $3.4 billion dollars and when deployed carries over 6,000 personnel onboard. Considering the cost and the man hours involved in carrier operations, judicious and effective use of these valuable assets is imperative.

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The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power" (OPNAV INSTRUCTION 3501.316, February 1995). To meet this mission, the Navy deploys aircraft carrier battle groups (CVBGs) to forward positions. Globally the Navy attempts to maintain the forward presence of aircraft carriers in four major Areas of Responsibilities (AORs): the Eastern Atlantic, Mediterranean Sea, Indian Ocean/Persian Gulf and the Western Pacific (WESTPAC). Carriers from the Atlantic Fleet (LANTFLT) provide forward presence requirements for the Atlantic and Mediterranean AORs. Likewise, the Pacific Fleet (PACFLT) carriers provide coverage to WESTPAC and the Indian Ocean/Persian Gulf AORs. Occasionally, an Atlantic Fleet carrier will also assist in covering the Persian Gulf AOR.

Historically, the Navy has tried to maintain a continuous forward presence in all of the major AORs. The dwindling defense budget has limited the number of carriers available to meet this goal. Carrier availability is further constrained by scheduled maintenance, training requirements and the Chief of Naval Operation's (CNO's) policy on personnel tempo of operations (PERSTEMPO/OPTEMPO). These restrictions along with limited available assets have made continuous carrier coverage of all the AORs impossible.

Realizing the limitations of a smaller carrier force, the Chairman of the Joint Chiefs of Staff (CJCS) has developed the Global Naval Force Presence Policy (GNFPP). The GNFPP establishes the minimum requirements for the forward presence of aircraft carriers and Amphibious Ready Groups (ARGs). An ARG consists of the ships that carry a Marine Expeditionary Unit (MEU) and equipment required for conducting amphibious landings. Among other requirements, the GNFPP establishes the minimum number of days in a year a carrier must be present in a particular AOR and the maximum number of days an AOR can go without a CVBG or ARG on-station.

Aircraft carrier deployment scheduling is the process by which the Navy's carriers are assigned to provide coverage to the AORs. The CINCPACFLT Operations Department is responsible for scheduling deployments for the six carriers belonging to PACFLT. The aircraft carrier is the military's most valuable asset. A new nuclear powered carrier costs over $3.4 billion dollars and when deployed carries over 6000 personnel onboard (Jane's Fighting Ships, 1995). Considering the cost and the man hours involved in carrier operations, judicious and effective use of these expensive assets is imperative. Currently, the carrier deployment schedule is produced manually. A feasible long-range deployment schedule (i.e., a five year plan) typically takes the operations department one week to generate. The goal of this study is to develop an optimization based tool to assist in constructing deployment schedules for PACFLT carriers and ultimately to increase their operating effectiveness.

This study develops a computerized system, known as the Pacific Fleet Aircraft Carrier Scheduler (PACACS), to aid in the scheduling of PACFLT aircraft carrier

deployments. The system is based on an optimization model that is quite different from those in the literature. Instead of using the set covering approach, the problem is formulated as a shortest path problem with side constraints. This allows the problem to be solved more rapidly, thus allowing more time for sensitivity and trade-off analyses.

To validate and illustrate its speed, the PACACS system was used to develop a five year deployment plan using inputs provided by the CINCPACFLT Operations Department. The system produced a weekly deployment schedule in less than 33 CPU seconds on a 60 MHz Pentium personal computer. When compared to the manually produced deployment plan, the one generated by PACACS has the following advantages:

1. PACACS' deployment schedule provides more coverage to the AORs. In particular, PACACS' increases the coverage of the AORs by 49 days.

2. PACACS' deployment schedule has shorter gaps. PACACS decreases the longest length time during which there is no carrier coverage of the AORs by 14 days.

3. PACACS provides a schedule in less than 33 seconds after entering the required information. The manual approach requires 7 days to produce a schedule.

4. A feature in PACACS allows it to generate schedules that minimizes changes to the already published schedule. Changes to the published schedule are often disruptive and may induce frustration with and distrust of the scheduling process.

PACACS solves an important problem for the Navy, that is how to most effectively utilize its most expensive and limited asset, the aircraft carrier. Certainly, PACACS can also be applied to the scheduling of the LANTFLT carriers. However, a more interesting direction would be to combine the scheduling of the two fleets in order to further enhance the effectiveness of the entire Naval fleet of carriers.

I. INTRODUCTION

The Navy's peacetime mission is "to conduct forward presence operations to help shape the strategic environment by deterring conflict, building interoperability, and by responding, as necessary, to fast breaking crises with the demonstration and application of credible combat power" (OPNAV Instruction 3501.316, 1995). To meet this mission, the Navy attempts to maintain the forward presence of aircraft carriers in four major Areas Of Responsibilities (AORs): the Eastern Atlantic, Mediterranean Sea, Indian Ocean/Persian Gulf and the Western Pacific (WESTPAC). Carriers from the Atlantic Fleet (LANTFLT) provide forward presence requirements for the Atlantic and Mediterranean AORs. Likewise, the Pacific Fleet (PACFLT) carriers provide coverage to WESTPAC and the Indian Ocean/Persian Gulf AORs. Occasionally, an Atlantic Fleet carrier will also assist in covering the Persian Gulf AOR.

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Realizing the limitations of a smaller carrier force, the Chairman of the Joint Chiefs of Staff (CJCS) has developed the Global Naval Force Presence Policy (GNFPP). The GNFPP establishes the minimum requirements for the forward presence of aircraft carriers and Amphibious Ready Groups (ARGs). The latter consists of the amphibious ships that

carry Marines and equipment required for conducting amphibious landings. Among other requirements, the GNFPP establishes the minimum number of days in a year a carrier must be present in a particular AOR and the maximum number of days the AOR can go without an aircraft carrier or ARG on-station. (Global Naval Force Presence Policy, 1995).

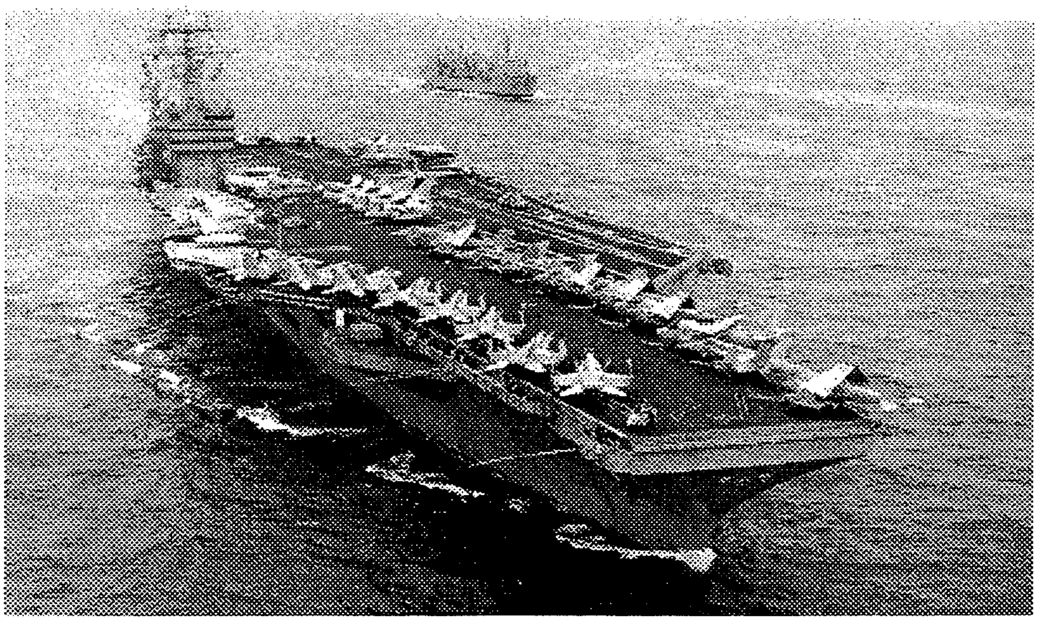

Figure 1.1. U.S.S. Abraham Lincoln (CVN 72), Nimitz Class Aircraft Carrier

A. PROBLEM STATEMENT

The U.S.S. Abraham Lincoln (CVN 72), Figure 1.1, is the newest nuclear powered aircraft carrier in the Pacific Fleet. A new nuclear powered carrier costs over $3.4 billion dollars and when deployed carries over 6,000 personnel onboard (Jane's, 1995). Considering the cost and the man-hours involved in carrier operations, scheduling deployments for these carriers significantly impact not only the U.S. defense strategy; but also impacts the Navy financially. Unnecessary delays and inefficient deployment of the

carriers only contribute to a wasteful usage of resources and a degraded display of combat power. Currently, the deployment scheduling procedure is performed manually. At CINCPACFLT, the Operations Department is responsible for scheduling deployments for its six carriers. A feasible long-range deployment schedule (i.e., a five year plan) typically takes the department one week to generate. The goal of this thesis is to develop an optimization based tool to assist in constructing deployment schedules for PACFLT carriers that will ultimately increase their operating effectiveness.

B. THESIS OUTLINE

Chapter II describes aircraft carrier operations at CINCPACFLT. Chapter III formulates the carrier deployment scheduling problem and discusses its solution property. Chapter IV presents a Windows based implementation to facilitate schedule generation analysis. Finally, Chapter V provides conclusions and recommendations for future research.

II. AIRCRAFT CARRIER OPERATIONS

CINCPACFLT is responsible for providing aircraft carrier coverage to two AORs, WESTPAC and the Persian Gulf. At the present time, the PACFLT has six aircraft carriers available to provide coverage. These six aircraft carriers are the Independence, Kitty Hawk, Constellation, Nimitz, Carl Vinson and Abraham Lincoln. Currently, the Independence is homeported in Yokosuka, Japan. When the Independence decommissions in 1998, the Constellation will become the carrier homeported in Japan and PACFLT will receive a new carrier, the John C. Stennis. Although, the Yokosuka based carrier mainly covers the WESTPAC, it must deploy on occasions to the Persian Gulf in order to meet GNFPP requirements. The remaining PACFLT carriers are homeported in California and Washington. Two carriers are homeported in San Diego, California, and in Washington, there are two in Bremerton and one in Everett (see Figure 2.1).

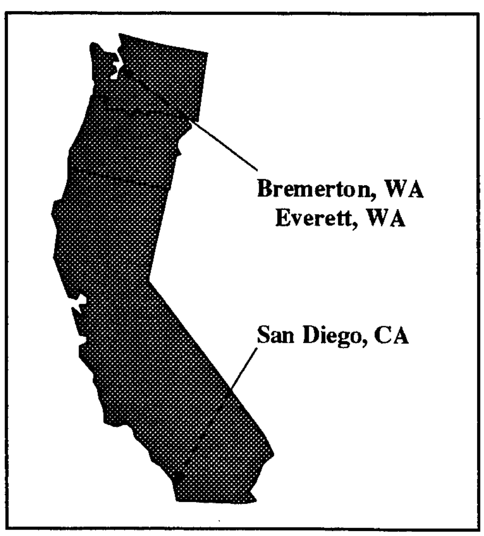

Figure 2.1. Carrier Homeports

The scheduling of these six carriers depends on five factors: (i) depot level maintenance, (ii) work-up cycle, (iii) personnel tempo of operations, (iv) transit time, and (v) availability of LANTFLT carriers. Each of these factors are described below.

A. DEPOT LEVEL MAINTENANCE

Depot level maintenance is define as "that maintenance which requires skills or facilities beyond those of the organizational and intermediate levels and is performed by naval shipyards, naval ships repair facilities, or item depot activities" (OPNAV Instruction 4700.7J, 1992). While at depots, carriers undergo large scale maintenance, repairs, approved alterations, and modifications to update and improve the carrier's technical and military capabilities. These maintenance periods can last from three months to three years depending upon the type of work scheduled.

The maintenance schedule for all surface combatants is maintained in the Fleet Modernization Program Management Information System (FMPMIS). Since maintenance of these combatants require much planning and preparation on the part of the maintenance facilities, the FMPMIS contains maintenance schedules for each ship for a ten year period. Typically, the near term schedules are firm. Changes to near term schedules often create disruptions and are discouraged. On the other hand, schedules in the more distant future are more flexible. The carrier deployment scheduling officer at the CINCPACFLT Operations Department may request a start date of a distant maintenance period be moved up or pushed back as much as several weeks.

B. WORK-UP CYCLE

After depot level maintenance and prior to deployment, all ships are required to execute the Tactical Training Strategy (TTS) which occurs during the period known as the work-up cycle. This work-up cycle is designed to ensure that the crew is properly trained and that the ship is ready for deployment. The ideal amount of time necessary to execute the TTS and other requirements during work-ups is twelve months. Quite often a carrier cannot be allotted twelve months for work-ups due to operational requirements and must compress the work-up cycle into fewer months. As a measurement of this compression, the Work-Up Factor (WUF) is defined as the ratio of the number of months available for training (i.e., the number of months from the end of depot level maintenance to deployment) divided by 12. CINCPACFLT will accept a WUF as low as .7 and still expect a ship to be able to perform adequately on deployment. (Trip Report, 1994.) This minimum WUF equates to an additional 8.4 months after depot level maintenance that the aircraft carrier is unavailable for deployment.

C. TEMPO OF OPERATIONS

To ensure a balance between the support of national objectives and reasonable operating conditions for naval personnel, the CNO initiated the Personnel Tempo of Operations (PERSTEMPO) program. The PERSTEMPO program accomplishes this balance by placing peacetime utilization limitations on all Naval units which deploy from their homeport. There are three utilization limitations:

1. The maximum length of a deployment cannot exceed six months (180 days).

2. There must be a minimum of 2 to 1 Turn Around Ratio (TAR) between deployments. This means that a carrier must remain home for at least 12 months following a six month deployment.

3. Over a five year cycle (three years historical, two years projected) a carrier must spend a minimum of 50% of its time in homeport.

A carrier cannot deploy unless it satisfies these PERSTEMPO restrictions. (OPNAV Instruction 3000.13A, 1990).

D. SCHEDULING OF PACFLT CARRIERS AND ARGS

Members of the CINCPACFLT operations department attend a regularly held conference with the scheduling officers from CINCLANTFLT. During this conference, the LANTFLT schedulers announce the times the LANTFLT carriers will be able to cover the Persian Gulf. Typically, the LANTFLT carriers cover the gulf twice a year with 30 to 45 days on-station each time. CINCPACFLT then schedules its carriers to cover the gulf for the rest of the year, if possible. To ensure maximum usage, CINCPACFLT adopts a practice of scheduling a deployment for a carrier only if it can be deployed for the maximum 180 days.

Recall that CINCPACFLT is responsible for two AORs, Persian Gulf and WESTPAC. When the five carriers homeported in the continental United States (CONUS) deploy, they must transit through the western part of the Pacific Ocean (i.e., WESTPAC) on their way to and from the Persian Gulf. Using a 14 knot speed of advance (SOA), this transit provides 30 days of *free* coverage for the WESTPAC AOR in each

direction. Since the Yokosuka based carrier's main mission is to cover WESTPAC, this free coverage further lessens the emphasis on WESTPAC when scheduling the carriers.

CINCPACFLT relies mainly on the five CONUS based carriers to cover the Persian Gulf AOR. The Yokosuka based carrier is used to cover the Persian Gulf when the GNFPP requirements cannot be fulfilled by the others. In scheduling the CONUS carriers, the schedulers must take into account the maintenance periods, TAR, WUF and the transit time to the gulf. Using, as before, the 14 knot SOA and allowing for ten days of quality of life port visits enroute, the transit time from CONUS to the gulf is approximately 45 days. This 45 day transit includes 15 days to transit from the carrier's homeport to WESTPAC and the 30 days of transit through WESTPAC. Taking into account the 180 day limit on deployment, the transit time to and from the gulf only leaves 90 days for a CONUS based carrier to remain on-station in the gulf. The scheduling officer must sequence the departure of the CONUS based carriers so that their 90 day on-station periods form a continuous coverage of the gulf. When gaps exist, they should be no larger than the GNFPP specified limit. When this is not possible, the Yokosuka based carrier can be used to cover the gulf when it is not covering WESTPAC, in maintenance, or limited by the TAR and WUF factors. To avoid long homeport time (e.g., one year), CINCPACFLT generally schedules the Yokosuka based carriers to cover the gulf only three weeks at a time.

Alternately, in order to meet the maximum allowed gap restriction, the GNFPP also allows an Amphibious Ready Group (ARG) to provide a coverage for the AOR. At CINCPACFLT, the deployment scheduling of the ARGs is secondary to that of the carriers. Typically, an ARG can deploy either three weeks before or three weeks after a

carrier is scheduled to deploy. At most this can decrease the gap in coverage to the AOR by 42 days. In Figure 2.2, the maximum decrease is achieved by deploying ARG-1 three weeks after carrier-1 and ARG-2 three weeks before carrier-2. Considering this scheduling practice, the next chapter focuses on the carrier deployment scheduling problem.

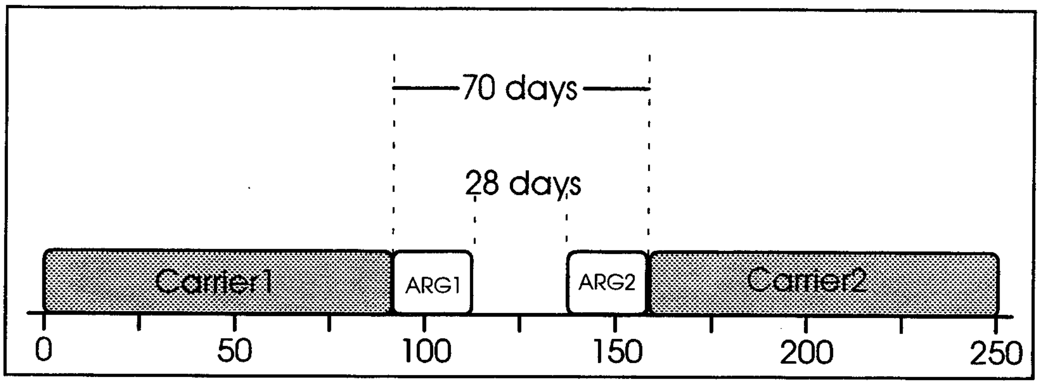

Figure 2.2. An ARG Deployment Strategy

III. CARRIER DEPLOYMENT SCHEDULING PROBLEM

As described in the last chapter, the problem of providing carrier presence to the CINCPACFLT's AORs can be reduced to the problem of scheduling carrier coverage of the Persian Gulf using mainly the five CONUS based carriers. The sections below (i) describe the problem in a conceptual framework, (ii) discuss related research and (iii) present a mathematical formulation along with its solution properties.

A. PROBLEM DESCRIPTION

Figure 3.1 below displays a sample three year maintenance schedule for the five CONUS based carriers: Kitty Hawk (Kitty), Constellation (Conny), Nimitz, Carl Vinson and the Abraham Lincoln. The dark shaded cells indicate time in maintenance for each carrier. Following each maintenance period is a sequence of light shaded cells to indicate the required nine month work-up cycle. When the period between the end of one work-up cycle and the next maintenance is at least six months or 180 days long, then a deployment is possible and Stone (1990) refers to it as a *deployable period.* Otherwise, it is a *non-deployable period.* In Figure 3.1, a deployable period is unshaded and a non-deployable period is shaded black. To satisfy the TAR and WUF factors, only one deployment is allowed during each deployable period. In the sample maintenance plan, the Kitty Hawk has one deployable period lasting from September of 1997 to December of 1998. Since the Kitty Hawk can be deployed only once, a large number of schedules are possible. Using the 45 days transit time, one schedule is to have the Kitty Hawk depart its homeport on September 15th of 1997 and arrive in the Persian Gulf on November 1st of 1997.

After spending 90 days on-station in the gulf, it can depart the gulf on February 1st of 1998 and arrive back at its homeport on March 15th of 1998. By moving up or pushing back the first departure date, one can easily generate all possible schedules for each deployable period. The carrier deployment scheduling problem is to select one schedule from each deployable period so that, in combination, the selected schedules form a satisfactory coverage of the Persian Gulf.

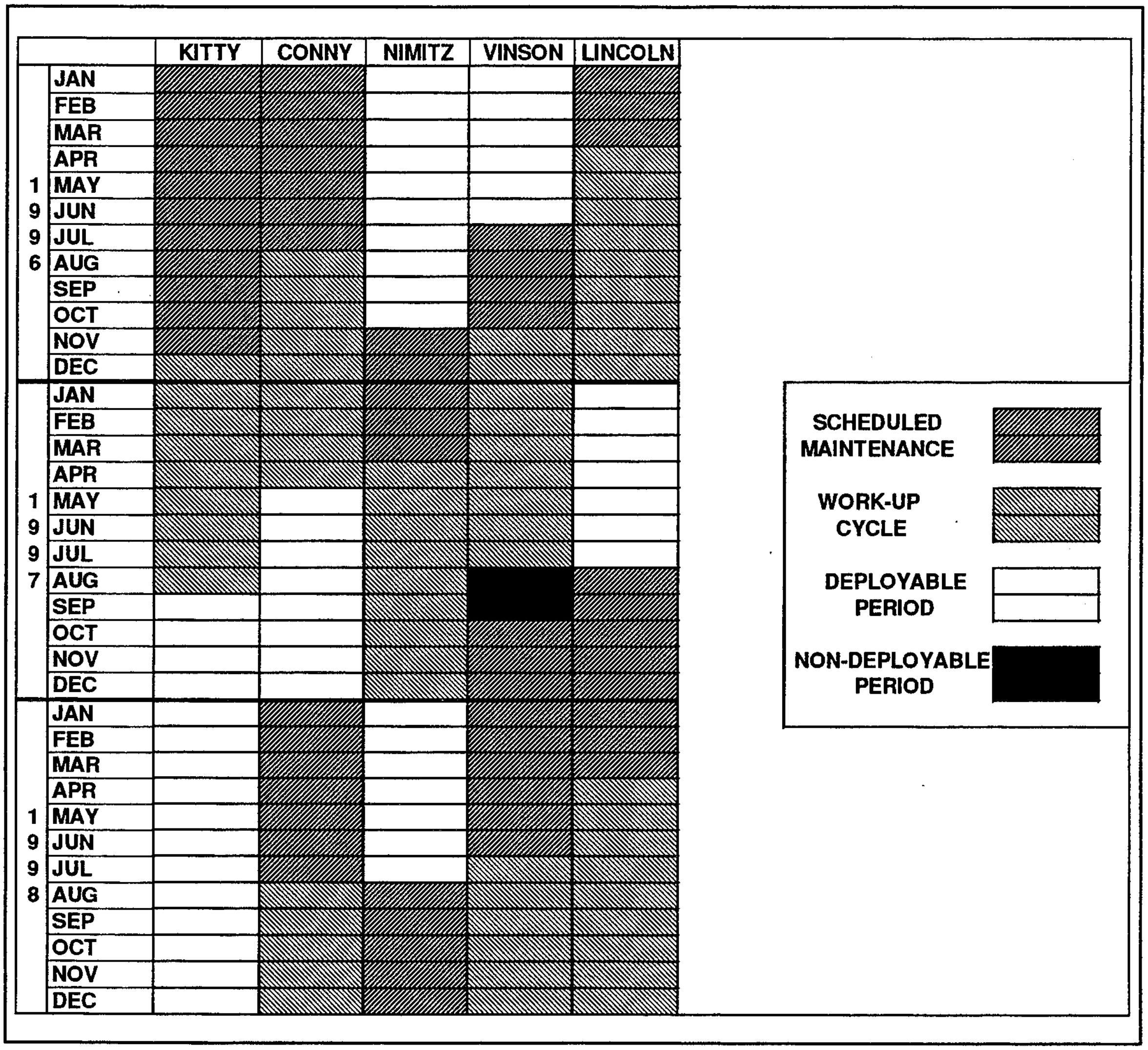

Figure 3.1. Maintenance Schedule and Deployable Period

Conceptually, each schedule can be represented as a vector of zeros and ones. If the k^{th} element of the vector is one, it indicates that the carrier is on-station in the gulf on the k^{th} time period of the planning horizon and a zero indicates that it is not. Table 3.1 provides an example of *on-station schedules* in a monthly resolution for a planning horizon of 1.5 years. (Note that zeros are left blank in this table). Columns labeled K1 to K6 are on-station schedules for the Kitty Hawk, C1 to C3 are for the Constellation, N1 and N2 are for the Nimitz and L1 and L2 are for the Lincoln. These schedules are from one deployable period of each ship and only one can be selected from each group. Selecting schedules K2, C3, N2 and L1 would leave January, February, June, July and August uncovered in the first year and March uncovered in the second year. In Table 3.1, these uncovered months are left blank in the column labeled COVERAGE. This leaves a maximum *coverage gap* of three months in the first year. If a three month gap is allowed by the GNFPP requirement, then a feasible schedule is found and the carrier deployment scheduling problem is solved. Otherwise, other combinations of schedules must be considered.

		K1	K2	K3	K4	K5	K6	C1	C2	C3	N1	N2	L1	L2	COVERAGE
	JAN														
	FEB														
	MAR												1		1
	APR												1	1	1
1	MAY												1	1	1
9	JUN													1	
9	JUL							1							
7	AUG							1	1						
	SEP							1	1	1					1
	OCT								1	1					1
	NOV	1								1					1
	DEC	1	1												1
	JAN	1	1	1											1
1	FEB		1	1	1										1
9	MAR			1	1	1					1				
9	APR				1	1	1				1	1			1
8	MAY					1	1				1	1			1
	JUN						1					1			1

Table 3.1. On-Station Schedules

B. RELATED WORK

As described above, the carrier deployment problem is related to the well known set-covering or set-partitioning problem. (See, e.g., Baush, 1982.) Many have formulated the problem of scheduling vehicles or transportation assets such as delivery trucks, buses, oil tankers and ships as a set-covering or partitioning problem. For military applications, Wing (1986) developed a program called SURFSKED to schedule surface combatants for inspections, training and other events. Brown, Goodman and Wood (1990) developed a similar program called CPSKED to assign combatants to deployments and naval exercises that have been previously scheduled. Stone (1990) used the set-covering approach to determine the minimum number of LANTFLT carriers to provide coverage to the Mediterranean AOR. For industrial applications, Brown, Graves and Ronen (1987) solved the crude oil tankers scheduling problem via the set partitioning approach. Prior to

this work, Appelgren (1969, 1971) and Crawford and Sinclair (1977) also considered an approach with the same framework as the set-covering or partitioning problem to schedule ships and beer tankers.

Besides the set-covering or partitioning approach, others also formulated the scheduling of transportation assets as a linear integer program. Two survey articles, Bodin (1990) and Ronen (1983) (and references cited therein) discuss various models and applications. In addition to these studies, Sibre (1977) considered a ship scheduling in which the interactions between schedules are nonlinear and Whalen (1995) analyzed surface combatant force structure requirements via a heuristic method and a spreadsheet.

The formulation of the carrier deployment scheduling problem in the next section is related to the set-covering or partitioning approach in that all the schedules are assumed to be previously generated. However, instead of solving an integer programming problem to obtain an optimal set of schedules, the problem is formulated as a shortest path problem with side constraints

C. PROBLEM FORMULATION

The carrier deployment scheduling problem is a feasibility problem because it tries to find of a (feasible) combination of schedules that leaves coverage gaps no larger than a specified (e.g., by the GNFPP) amount which is referred to as *max-gap*. When a feasible combination of schedules is sequenced in a chronological order, every two successive on-station schedules must satisfy the following conditions:

1) They must belong to different deployable periods,

2) One schedule must depart before the other, and

3) The coverage gap between them does not exceed max-gap.

When the two on-station schedules satisfy these three conditions, they are said to be *compatible*. Under the assumption that the transit time to and from the gulf is the same (e.g., 45 days) for all carriers, the second condition ensures that no two ships will cover the gulf in the same 90 day period.

Table 3.2 provides the coverage gaps between the on-station schedules in Table 3.1 that satisfy conditions (1) and (2). Blank entries indicate that condition (1), (2), or both are not satisfied. For example, a value of 1 in the cell (K1, N1) indicates that there is a gap of one month, if schedule N1 is to follow schedule K1.

	K1	K2	K3	K4	K5	K6	C1	C2	C3	N1	N2	L1	L2
K1										1	2		
K2										0	1		
K3										0	0		
K4										0	0		
K5											0		
K6													
C1	1	2	3	4	5	6							
C2	0	1	2	3	4	5							
C3	0	0	1	2	3	4							
N1						0							
N2													
L1	5	6	7	8	9	10	1	2	3	9	10		
L2	4	5	6	7	8	9	0	1	2	8	9		

Table 3.2. Coverage Gap Between Pairs of On-Station Schedules

Using a max-gap of two months, elements with coverage gaps greater than two are considered incompatible. Table 3.3 uses the number '1' to indicate pairs of compatible schedules.

	K1	K2	K3	K4	K5	K6	C1	C2	C3	N1	N2	L1	L2
K1										1	1		
K2										1	1		
K3										1	1		
K4										1	1		
K5											1		
K6													
C1	1	1											
C2	1	1	1										
C3	1	1	1	1									
N1						1							
N2													
L1							1	1					
L2							1	1	1				

Table 3.3. Compatibility Between Pairs of On-Station Schedules

Observe that table 3.3 has a structure of a node-node adjacency matrix of a network (see, e.g., Ahuja, Magnanti and Orlin, 1993) in which a node represents an on-station schedule and an arc indicates that two schedules are compatible. Note that arcs are directed from node *i* to node *j*, if schedule *i* departs before schedule *j*. Figure 3.2 shows the network representation of Table 3.3 with the addition of two auxiliary nodes, *s* and *t*, to signify the start and finish of the planning horizon.

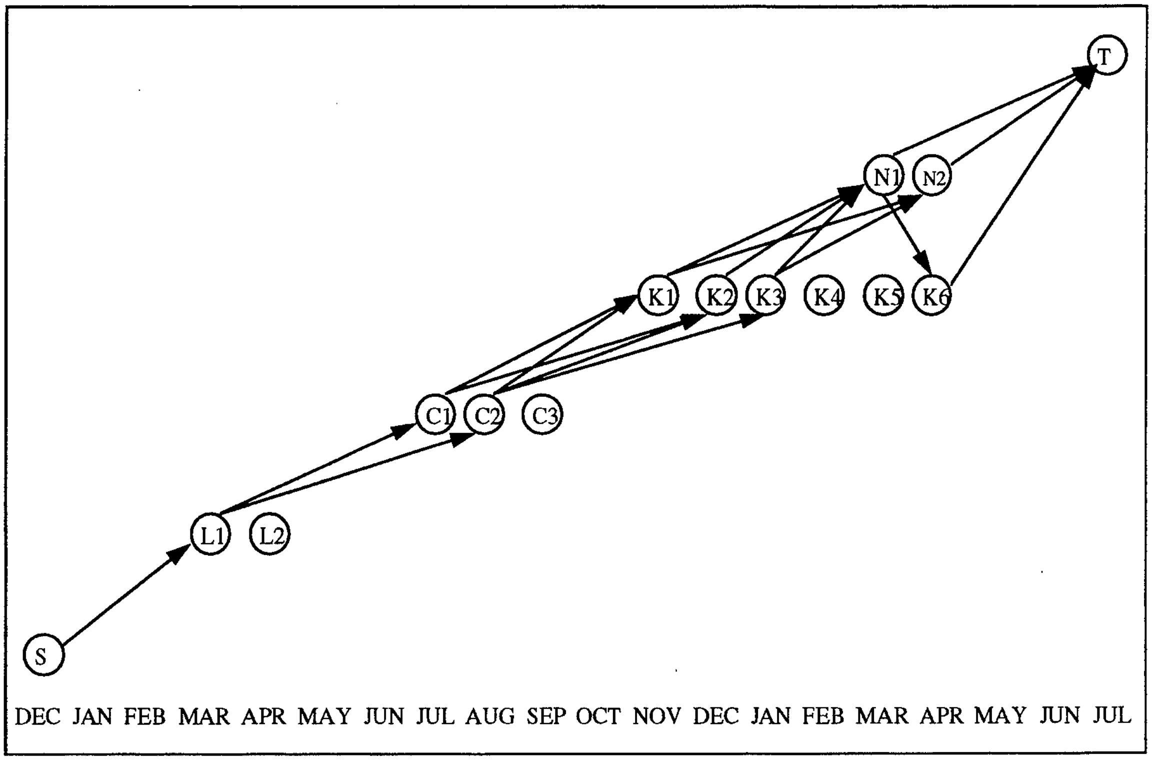

Figure 3.2. Network Representation

An arc from node s to a node representing schedule i (or schedule node i) is added to the network, if the gap between the start of the planning horizon and the beginning of schedule i does not exceed max-gap. Similarly, there is an arc for schedule node i to node t, if the gap between the end of schedule i and the end of the planning horizon does not exceed max-gap. Loosely speaking, there is an arc from s to i, if node s is said to be compatible with schedule i. Similarly, there is an arc from i to t, if schedule i is compatible with node t. The absence arcs terminating or eminating from a schedule node i, indicates that schedule i is not compatible with any other schedule.

With the above network representation, a feasible combination of schedules that satisfies max-gap corresponds to a path from s to t that visits at most one node or schedule in each deployable period. For example, a path s - L1 - C1 - K1 - N1 - t for the

network in Figure 3.2 is a feasible path, i.e., it corresponds to a feasible combination of schedules. However, in an effort to generate a feasible combination which leaves the gulf uncovered for the least amount of time, a cost or length is added to each arc. These costs are simply the length of the coverage gap between two compatible schedules or between a schedule and nodes s or t. With these arc costs, scheduling carriers for deployment becomes the problem of finding a feasible path from s to t with the least cost. This problem can be stated mathematically as follows:

INDICES:

c	aircraft carriers
d	deployable periods
i	nodes in the network
j	alias index for i.

INDEX SET:

Ω_c^d = $\{i$: node i belongs to deployable period d of carrier $c\}$

DATA:

g_{ij}	the gap between node i and node j
a_{ij}	equals 1 if there exists an arc from node i to node j

BINARY DECISION VARIABLES:

X_{ij}	equals 1 if arc (i,j) belongs to the shortest path (0 otherwise)

FORMULATION:

The Carrier Deployment Scheduling (CDS) Problem

Minimize: $$\sum_{\{(i,j):a_{ij}=1\}} g_{ij} X_{ij}$$

Subject to:

$$\sum_{\{j:a_{ji}=1\}} X_{ji} - \sum_{\{j:a_{ij}=1\}} X_{ij} = \begin{cases} -1 & \text{if } i = s \\ 1 & \text{if } i = t \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

$$\sum_{\{i \in \Omega_c^d\}} \sum_{\{j:a_{ij}=1\}} X_{ij} \leq 1 \quad \forall\ c,d \qquad (2)$$

In the above formulation, the objective function minimizes the total amount of time the AOR is not covered. Constraints (1) are the balance of flow constraints for each node in the network. Constraints (2) ensure that at most one on-station schedule is selected from each deployable period. If (2) is absent, the problem would reduce to the standard shortest path problem.

D. INTEGRALITY PROPERTY

During an initial implementation, the linear programming relaxation of the CDS problem always yields an integer solution. This is unexpected and encourages further investigation. First, it is well known (see, e.g., Nemhuaser and Wolsey, 1988) that, if the constraint matrix of a linear programming problem is totally unimodular, then a basic

solution to the problem is always integer. Moreover, a matrix A is totally unimodular if and only if the corresponding expanded matrix (A, I), where I is an identity matrix of an appropriate size, is totally unimodular. Considering this last fact, the CDS problem is modified by deleting the row corresponding to node s (which is redundant), adding artificial variables Y_i with a sufficiently large cost $M > 0$ to constraints in equation (1) and adding slack variables, W_{cd} , to constraints in equation (2). The resulting problem is as follows:

The Modified Carrier Deployment Scheduling Problem

Minimize: $$\sum_{\{(i,j):a_{ij}=1\}} g_{ij} X_{ij} + M \sum_{i \neq s} Y_i$$

Subject to:

$$\sum_{\{j:a_{ji}=1\}} X_{ji} - \sum_{\{j:a_{ij}=1\}} X_{ij} + Y_i = \begin{cases} 1 & if\ i = t \\ 0 & if\ i \neq s,\ t \end{cases} \qquad (3)$$

$$\sum_{\{i \in \Omega_c^d\}} \sum_{\{j:a_{ij}=1\}} X_{ij} + W_{cd} = 1 \quad \forall\ c,d \qquad (4)$$

$$X_{ij}, Y_i, W_{cd} \geq 0 \qquad \forall\ i, j, c, d$$

Graphically, Y_i represents an artificial arc with cost M from node s to node i in the network. In addition, the variable x_{ij} is no longer restricted to be either 0 or 1. Thus, the modified CDS problem can be considered as a linear programming relaxation of the original CDS problem.

Let A represent the constraint matrix corresponding to equations (1) and (2), and $\bar{A}$ represent A with the row corresponding to node s deleted. Then, constraints (3) and (4) have the form $(\bar{A}, I)$. The following example shows that $(\bar{A}, I)$ is not totally unimodular which in turn implies that A and $\bar{A}$ are not totally unimodular. Figure 3.3 shows a network representation of a CDS problem in which each of the two ships, Connie and Kitty, has only one deployable period and each ship has two on-station schedules.

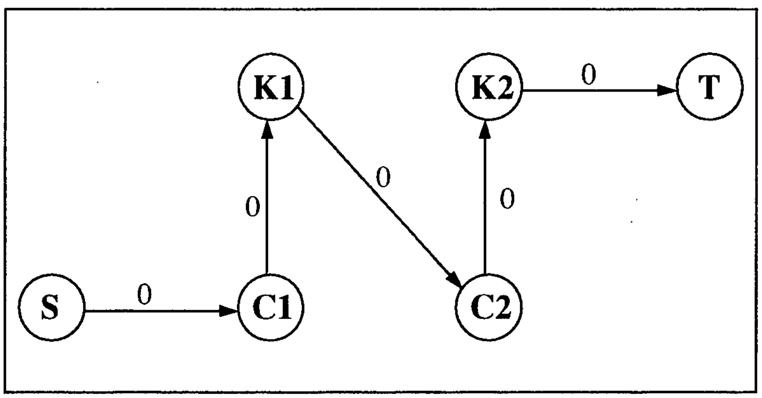

Figure 3.3. An Infeasible CDS Problem

Arcs in the network display compatibility among schedules, all of which have zero coverage gap. This CDS problem has no feasible solution. The only path from s to t requires all four schedules. However, this is not feasible since only one schedule can be selected for each ship. An optimal basic feasible solution (see Figure 3.4) to the modified CDS problem is:

$$X_{ij} = 0.5 \quad \forall\,(i,j)$$

$$Y_t = 0.5$$

$$Y_j = 0 \quad \forall\, j \neq t$$

$$W_{cd} = 0 \quad \forall\, c,d$$

and the optimal objective function value is 0.5 M. In general, ($\overline{A}$, I) is not a totally unimodular matrix.

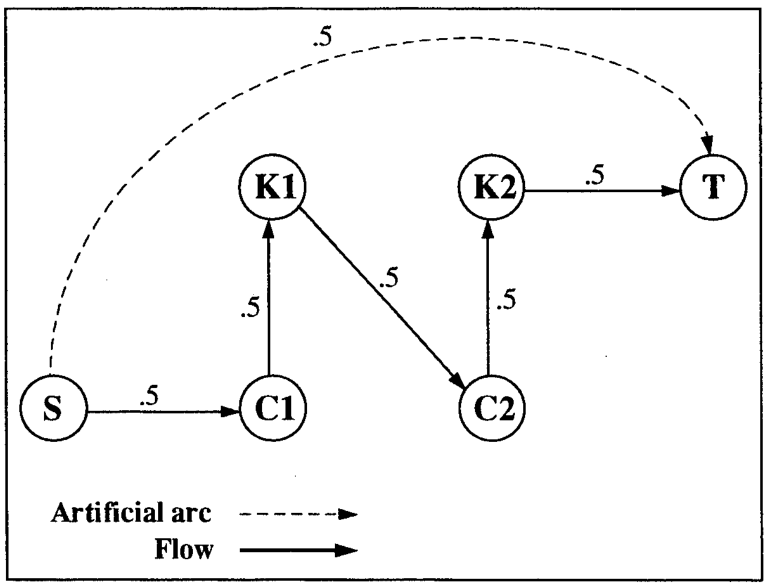

Figure 3.4. An Optimal Solution to the Modified CDS Problem

The above example does not explain the phenomenon that occurred during the initial experimentation. However, it establishes the fact that, if the CDS problem is not feasible, then its solution may not be integer. On the other hand, when the CDS problem is feasible, the following properties show that the simplex algorithm always produces an integer solution.

The following integrality properties of the CDS problem holds since the problem is concerned with the scheduling of carrier deployments to only one AOR.

Property 3.1: For every feasible solution to the original CDS problem, there exists a basic feasible solution to the modified CDS problem which is integer.

Proof: Let X denote a feasible solution to the CDS problem. Below, it is shown that a basic feasible solution for the modified CDS problem can be constructed from X. Observe that X must correspond to a directed path from s to t. Then, a feasible solution, $(\hat{X}, \hat{Y}, \hat{W})$, for the modified CDS problem can be constructed as follows:

1) Set $\hat{X}_{ij} = X_{ij}$ for all arcs (i, j) in the network.

2) Set $\hat{Y}_i = 0$ for all i.

3) Set $\hat{W}_{cd} = 1 - \sum_{\{i \,\varepsilon\, \Omega_c^d\}} \sum_{\{j: a_{ij}=1\}} X_{ij} \quad \forall\ c, d.$

The above solution is a basic feasible solution since the columns for the following variables are linearly independent and form a basis:

i) $\hat{X}_{ij}$ for all arcs (i, j) on the directed path from s to t,

ii) $\hat{Y}_i$ for all nodes i not on the directed path from s to t,

iii) $\hat{W}_{cd}$ for all c, d.

The basic variables $\hat{X}_{ij}$ and $\hat{Y}_i$, as chosen above, correspond to a spanning tree for the network. (See Figure 3.5). Thus, their columns must be linearly independent. The basic variable $\hat{W}_{cd}$ corresponds to a slack variable and its column must be linearly independent

from columns in $\overline{A}$. Variables not in (i), (ii) or (iii) are non-basic and have zero value by construction. Since each basic variable $\hat{Y}_i$ has zero value, the solution $(\hat{X}, \hat{Y}, \hat{W})$ corresponds to a degenerate basic feasible solution. Moreover, every component of $(\hat{X}, \hat{Y}, \hat{W})$ must be integer since every component of X is binary. Q.E.D.

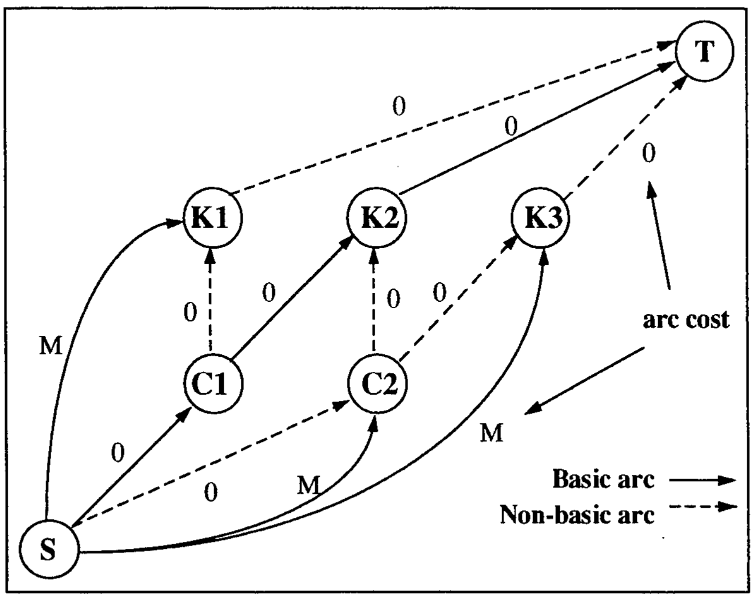

Figure 3.5. Spanning Tree for the Modified CDS Problem

Property 3.2: If the original CDS problem has a feasible solution, then there exist an optimal basic feasible solution to the modified CDS problem which is integer.

Proof: Since the original CDS problem has a feasible solution, there must exist an optimal solution, X^*. Construct a solution $(\hat{X}, \hat{Y}, \hat{W})$ for the modified CDS problem from X^* as in Property 3.1. By this construction, $(\hat{X}, \hat{Y}, \hat{W})$ is a basic feasible integer solution and,

furthermore, it has the same objective function value as X^*. Thus, $(\hat{X}, \hat{Y}, \hat{W})$ must also be optimal. Q.E.D.

Property 3.3: If the original CDS problem has a feasible solution, then the simplex algorithm must generate an optimal basic feasible solution which is integer.

Proof: Since the original CDS problem is feasible, $\hat{Y}_i$ must be zero for all i in an optimal solution to the modified CDS problem. Let $(\hat{X}, \hat{Y}, \hat{W})$ denote an optimal basic feasible solution generated by the simplex algorithm. Since

$$\hat{W}_{cd} = 1 - \sum_{\{i \in \Omega_c^d\}} \sum_{\{j:a_{ij}=1\}} X_{ij},$$

$\hat{W}_{cd}$ can be non-integer only if X_{ij} is non-integer. So, assume that X_{ij} is non-integer. Because equation (3) corresponds to the flow balance constraint for the network with artificial arcs, $\hat{X}$ must correspond to a flow of one unit from s to t along several paths. In other words, $\hat{X}$ is a convex combination of paths from s to t, i.e.,

$$\hat{X} = \sum_{k=1}^{K} \alpha_k P^k$$

where P^k is a (0,1) vector corresponding to a path from s to t, $\alpha_k \geq 0$ and

$$\sum_{k=1}^{K} \alpha_k = 1.$$

Since each P^k corresponds to a path from s to t, there must exist a corresponding basic solution via the construction in Property 3.1. However, this implies that $\hat{X}$ is a convex combination of basic solutions. This is not possible since the simplex algorithm examines basic feasible solutions one at a time. Thus, Property 3.3 ensures that the simplex algorithm always produces an optimal integer solution to the modified CDS problem.

Q.E.D.

IV. IMPLEMENTATION AND RESULTS

This chapter describes a Windows based software package called the Pacific Fleet Aircraft Carrier Scheduler or PACACS that automates the data input, solves the resulting CDS problem, and displays the output. The user interface for PACACS is implemented using Borland's Delphi for Windows (Borland Inc., 1995). The next two sections describe key features of PACACS and a sample problem. The third section analyzes two scheduling issues via solving the CDS problem. Finally, the fourth section presents a modification to generate persistent schedules, i.e., schedules which closely adhere to the already published schedules.

A. PACIFIC FLEET AIRCRAFT CARRIER SCHEDULER

Besides the title window, PACACS has one main window called the PACACS Control Window (PCW) to integrate the data input, solving the CDS problem and output display. There are four main options in PCW (See Figure 4.1): **File**, **Edit**, **View** and **Run**. Like most Windows application, the **File** option allows users to exit the program as well as to create, open, save and print files.

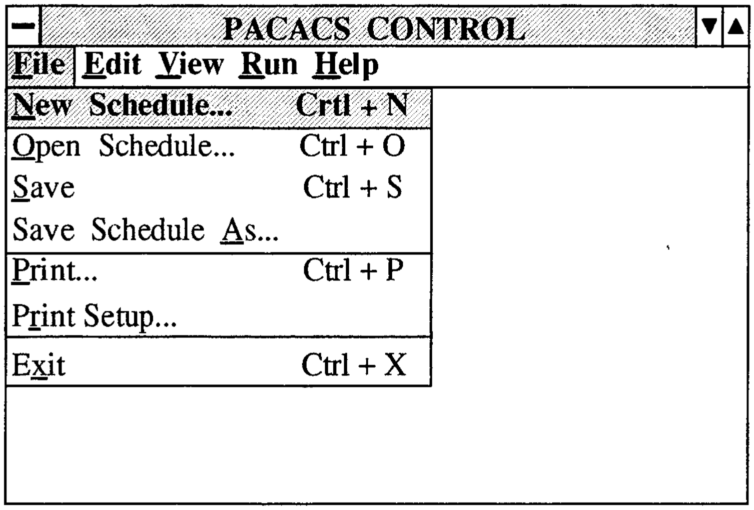

Figure 4.1. File Menu

The **Edit** option (See Figure 4.2) lets users enter new data and modify old ones.

There are five choices in the drop down menu for the **Edit** option:

Carrier: This choice lets the user view the current list of aircraft carriers stored in PACACS. Users can add and delete carriers from this list by entering the name of the carrier in the edit box and select the desired option inside the dialogue box. (See Figure 4.3)

Parameters: This choice lets the users view and enter new values for problem parameters. Clicking the down arrow next to the word *resolution* gives three choices: daily, weekly or monthly. Besides the problem resolution, the other parameters are the length of work-up cycle (in months), maximum allowable gap (in days), persistence factor (to be discussed in Section D), start and end date of the planning horizon. Note that it is common to state the work-up cycle length in months and maximum allowable gap in days. However, prior to solving the CDS problem, PACACS converts them into the same time unit as the chosen problem resolution. (See Figure 4.4)

Maintenance: This choice lets the user view the current scheduled maintenance dates for the carrier selected. Users can add and delete maintenance dates by entering the date in the edit box and clicking the desired button. (See Figure 4.5)

Published: This choice lets the user input the dates each carrier is already scheduled to arrive on-station as well as the dates each carrier returned from its last deployment. The latter date for calculating a carriers TAR. The issue concerning the published schedule is discussed in detail in Section D. (See Figure 4.6)

Coverage: This choice lets the user view the dates LANTFLT carriers are scheduled to provide coverage to the AOR. Similarly, if a PACFLT carrier is already on-station at the start of the planning horizon, its on-station coverage dates are entered in the coverage dialogue box. Users can add and delete dates as explained in the maintenance option. (See Figure 4.7)

(The parameter values shown in this chapter are fictitious.)

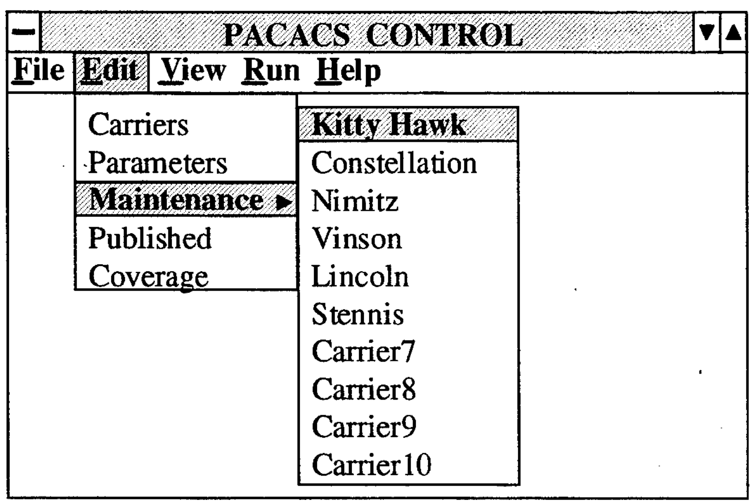

Figure 4.2. Edit Menu

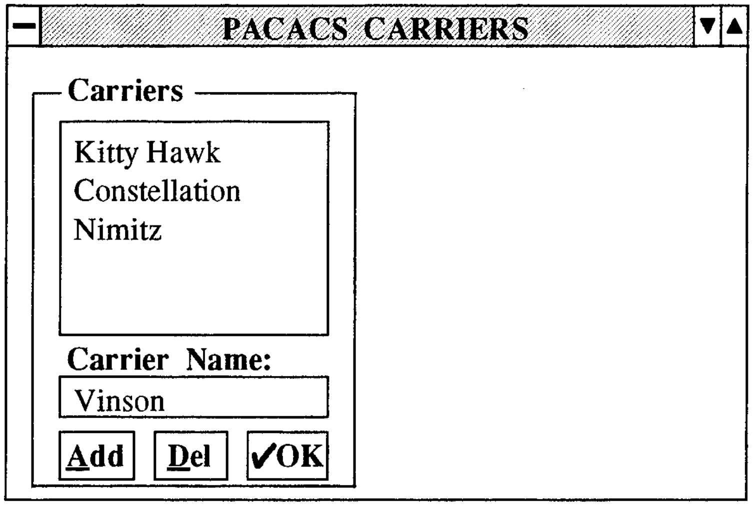

Figure 4.3 Carrier Dialogue Box

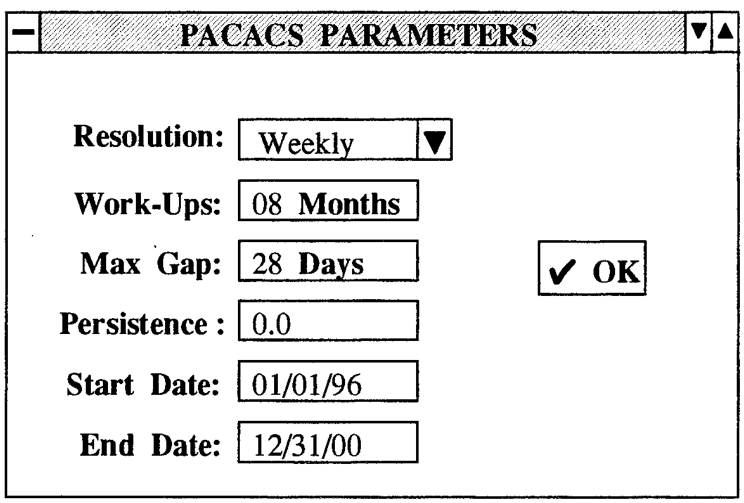

Figure 4.4. Parameter Dialogue Box

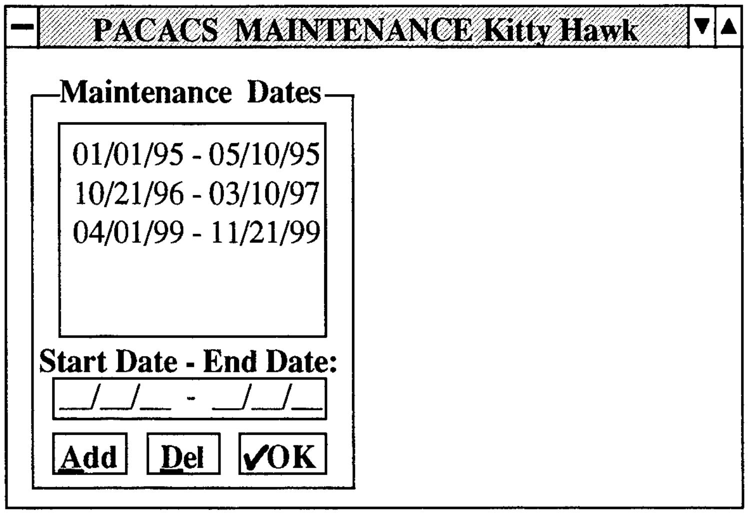

Figure 4.5. Maintenance Date Dialogue Box

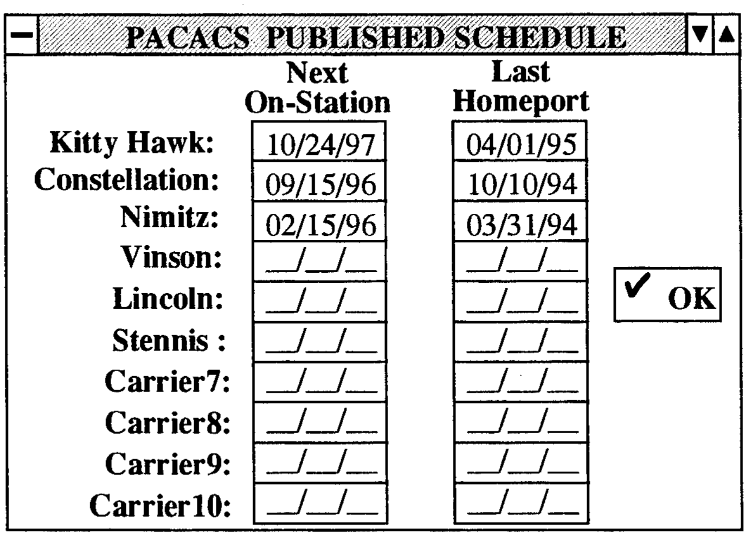

Figure 4.6. Published Schedule Dialogue Box

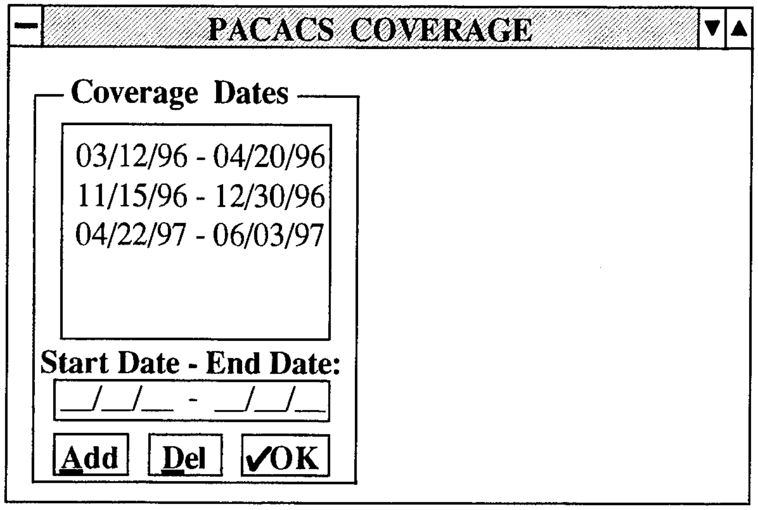

Figure 4.7. Coverage Dialogue Box

The **View** option (see Figure 4.8) lets users view the input and output files generated by PACACS. The input file contains a consolidation of all the input data. It is a legible representation of the input file required to solve the CDS problem. The output file is generated after the CDS problem has been solved and contains an optimal on-station schedule for the aircraft carriers. After the user correctly enters the necessary inputs, the **Run** option (see Figure 4.9) must be selected to solve the resulting CDS problem. Under the **Run** option, the user must select, in order, the following choices:

1) Generator: Generate the proper input for the solver. Under the current implementation, the Generator is written in Turbo Pascal 7.0 (Borland Inc.,1992) and produces a file in Mathematical Programming System (MPS) format.

2) Solver: Read the file generated by the Generator and execute the solver. The current version of PACACS uses MINOS 5.4 (Murtagh and Saunders, 1995) as the solver for the CDS problem.

3) Displayer: Convert the output from the solver into a readable format. The Displayer is also written in Turbo Pascal 7.0 (Borland Inc., 1992).

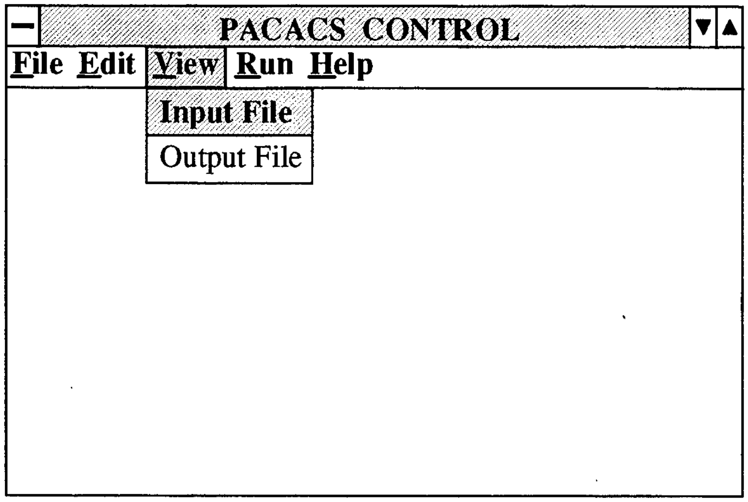

Figure 4.8. View Menu

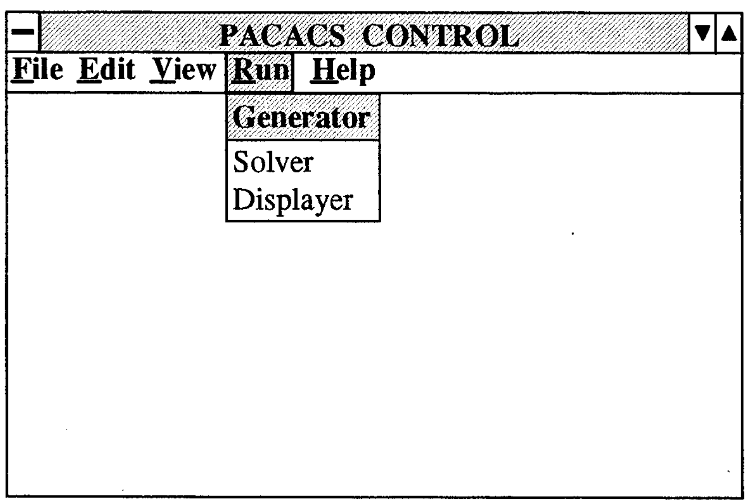

Figure 4.9. Run Menu

B. SAMPLE PROBLEM

To demonstrate its effectiveness PACACS is used to solve a sample problem with the following parameters:

Resolution = Weekly
Work-Ups = 8 months
Max Gap = 28 days
Persistence = 0.0
Start Date = 01/01/96
End Date = 12/31/00

The maintenance schedules are obtained from the FMPMIS and allow at most two deployable periods for each carrier during the five year planning horizon. Table 4.1 list the number of possible on-station schedules for each ship in each deployable period. Based on the data in Table 4.1, there are over 29 trillion combinations of on-station schedules, some of which may not be feasible. However, the Generator in PACACS generates a CDS problem with only 353 constraints and 6168 variables. MINOS requires less than 33 CPU seconds to solve the problem on a Pentium 60 MHz PC.

	1ST DEPLOYABLE PERIOD	2ND DEPLOYABLE PERIOD
KITTY HAWK	43	29
CONSTELLATION	18	N/A
NIMITZ	8	N/A
CARL VINSON	36	63
ABRAHAM LINCOLN	64	1
JOHN C. STENNIS	22	51

Table 4.1. Number of Possible On-Station Schedules

Table 4.2 displays part of the output file for the sample problem. Dates in this file are listed as month, day and year.

```
START DATE:    1   1 2001

GAP: 1 WEEK

LANTFLT
   ON-STATION   :  1   8 2001
   OFF-STATION  :  2  19 2001

GAP: 0 WEEKS

VinsoA
   DEPART       :  1   8 2001
   TETHER IN    :  1  29 2001
   ON-STATION   :  2  19 2001
   OFF-STATION  :  5  28 2001
   TETHER OUT   :  6  18 2001
   RETURN       :  7   9 2001
   WUF          :  0.90
   TAR          :  3.27

GAP: 0 WEEKS

KittyA
   DEPART       :  4  16 2001
   TETHER IN    :  5   7 2001
   ON-STATION   :  5  28 2001
   OFF-STATION  :  9   3 2001
   TETHER OUT   :  9  24 2001
   RETURN       : 10  15 2001
   WUF          :  1.10
   TAR          :  3.08

GAP: 2 WEEKS

LANTFLT
   ON-STATION   : 10  29 2001
   OFF-STATION  : 12  10 2001
                 •
                 •
                 •
```

Table 4.2. Solution Output File

The first line in the file gives the starting date for the planning horizon – January 1, 2001. Next is a list of on-station schedules in a chronological order. As an example, the first on-station schedule is for a LANTFLT carrier that begins and ends its coverage on January 8th and February 19th, respectively. The output shows that there is a coverage gap of one

week between the start of the planning horizon and the first day of coverage by the LANTFLT carrier. The next on-station schedule is for the Vinson which relieves the LANTFLT carrier on February 19th, thereby creating no coverage gap. (The first five letters of the heading are the first five letters in the carrier's name and the sixth letter corresponds to the deployable period. So, VinsoA refers to the first deployable period for the Vinson.) To arrive on-station on February 19th, the Vinson must depart its homeport on January 8th. On January 29th, the Vinson, using a 14 knot SOA, arrives at a geographical location sufficiently close to the AOR and is considered to be *in tether*. The term *in tether* refers to the fact that the carrier is in an area close enough to quickly respond to any crisis in the AOR. After being on-station for 90 days (form February 19th to May 28th), the Vinson departs the AOR. It is out of tether and arrives home on June 18th and July 9th, respectively. To meet this on-station schedule, the Vinson uses a WUF of 0.90 and a TAR of 3.27, both of which are acceptable. The rest of this output lists the remaining schedules for the entire planning horizon and contains the same information as explained above. If the solution to the CDS problem is infeasible, then the output file simply reports this fact. It is then left to the user to adjust the input parameters to obtain feasibility.

C. APPLICATIONS

In addition to generating optimal deployment schedules, PACACS can be used as a tool in analyzing scheduling policies. To illustrate, two issues, one concerning the length of the work-up cycle and the other concerning the scheduled maintenance, are analyzed below.

1. Length of Work-Up Cycle

It is clear that there is a trade-off between the length of a work-up cycle and the amount of coverage CINCPACFLT can provide for the AOR. In fact, more time spent on work-ups means less on-station time. To quantify this trade off, the sample problem is resolved with work-up cycle length varied from eight to twelve months. Figures 4.10 and 4.11 display the results graphically. In Figure 4.10, the amount of coverage provided gradually decreases as the work-up cycle increases in length. Figure 4.11 shows that the longest gap between two on-station schedules increases drastically when the work-up cycle increases from eight to nine months in length. If the coverage gap cannot exceed four weeks, Figure 4.11 shows that a work-up cycle longer than eight months will not be feasible.

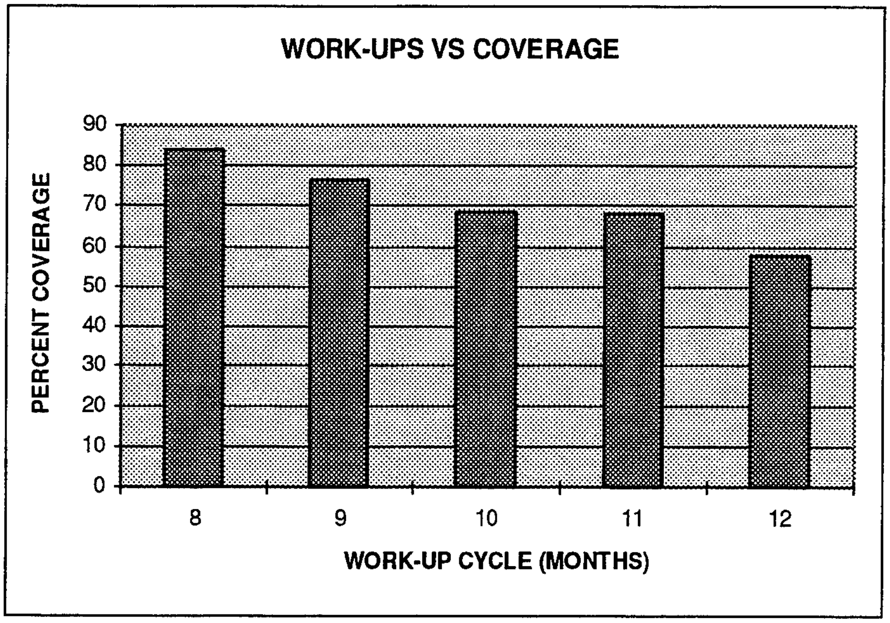

Figure 4.10. Trade-off Between Coverage and Work-Up Cycle

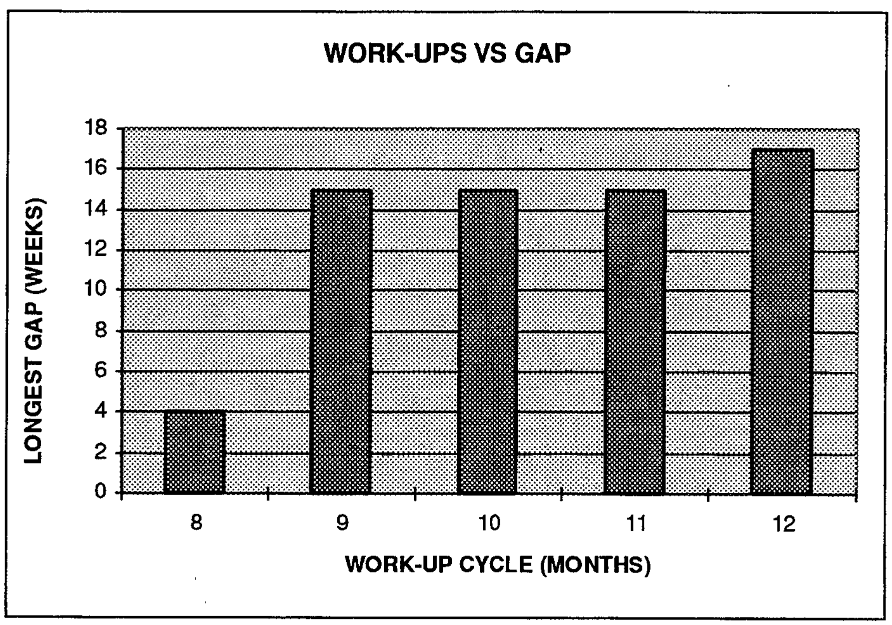

Figure 4.11. Trade-off Between Longest Gap and Work-Up Cycle

2. Scheduled Maintenance

As described in Chapter 2, ship maintenance are scheduled years in advance and it is not clear that the near time operational needs can be properly addresses when scheduling maintenance. From Figure 4.12, the largest gap in the sample problem using a nine month work-up cycle is 15 weeks which is unacceptable. Output from PACACS suggests that this gap can be shorten by delaying a scheduled maintenance period for the Abraham Lincoln in CY 2000 by one month. Figures 4.12 and 4.13 show that this delay in maintenance increases coverage by 9% and shortens the maximum gap by 73%.

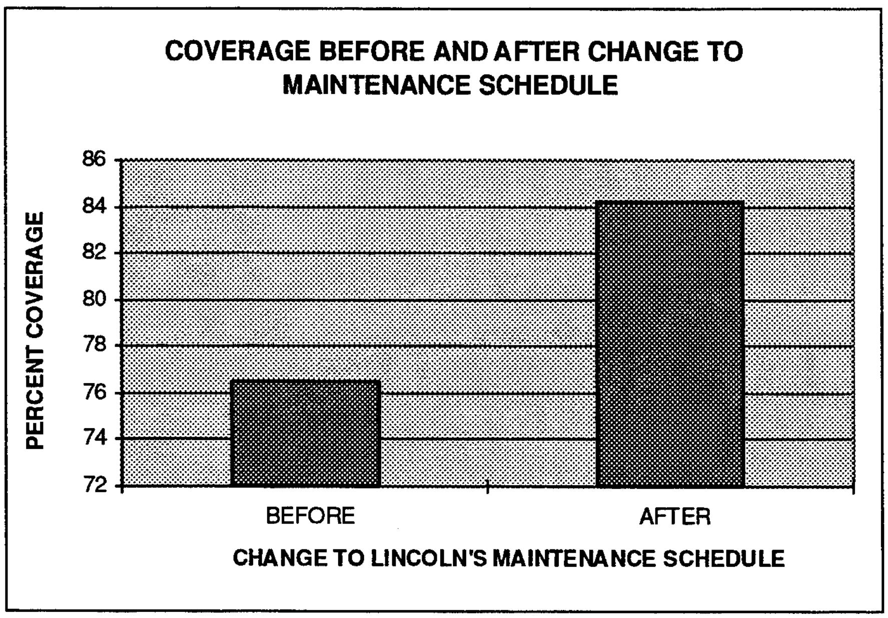

Figure 4.12. Effect of Maintenance on Coverage

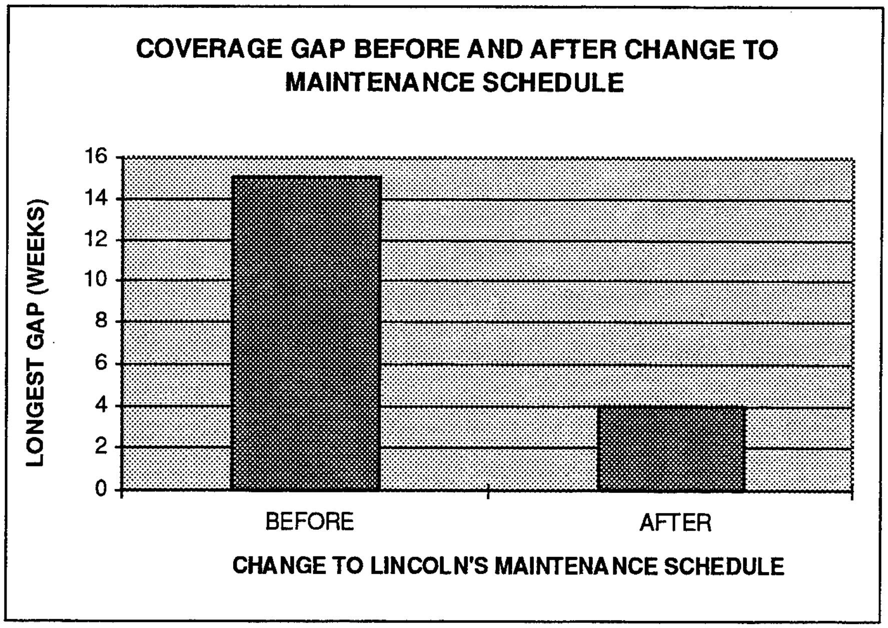

Figure 4.13. Effect of Maintenance on Longest Gap

D. PERSISTENCE

When an aircraft carrier deploys, it is typically escorted by six surface combatants belonging to the carrier battle group (OPNAV Instruction 3501.316, 1995). In addition, the squadrons belonging to the carrier air wing fly onboard the day after the carrier departs homeport. In short, the deployment of an aircraft carrier not only affects the carrier and its crews but also several others naval assets and the personnel assigned to them. The deployment of an aircraft carrier is a large undertaking requiring enormous amounts of coordination by numerous naval units and support activities. To ensure that there is enough time to allow for the necessary coordination, CINCPACFLT publishes and disseminates the deployment schedule for the next two years.

When planning carrier deployments, the operation department must try to maintain the already published schedule when it overlaps with the five year planning horizon.

Changes to the published schedule are disruptive and costly in terms of time, money and readiness. One approach to discourage changes is to penalize for deviations from the published schedule in the objective function. For each on-station schedule in the deployment period covered by the published schedule, let A_i denote the difference between the start date of on-station schedule i and that of the published schedule. The modification below uses A_i as a penalty for selecting schedule i.

ADDITIONAL DATA:

λ	persistence factor
A_i	length of time schedule i deviates from the published on-station schedule {If carrier c does not have a published on-station schedule in deployable period d, then $A_i = 0 \ \forall \ i \ \varepsilon \ \Omega_c^d$ }

NEW OBJECTIVE FUNCTION:

Minimize: $$\sum_{\{(i,j):a_{ij}=1\}} (g_{ij} + \lambda A_i) X_{ij}$$

The above objective function minimizes two terms, one involving the coverage gap, g_{ij}, between two on-station schedules and the other involving the deviation, A_i, from the published schedule. The persistence factor, λ, allows the user to control the amount of deviation. Larger values of λ would generate a deployment schedule with less deviation. When $\lambda = 0$, the deviation from the published schedule is ignored and the problem reduces to the original CDS problem stated in Chapter IV. Table 4.3 compares the effects of setting $\lambda = 1$ and $\lambda = 0$. When $\lambda = 1$, both the coverage gap and deviation must be minimized. The corresponding schedule provides 1,505 days of on-station coverage for the AOR, contains gaps that are no longer than 42 days in length and deviates from the published schedule by only one week. When $\lambda = 0$, only the coverage gap is minimized

and, as expected, the corresponding schedule has more on-station coverage and shorter gap lengths. However, since the deviation is ignored, $\lambda = 0$ generates a schedule that differs from the published schedule by 18 weeks.

	PERSISTENCE	
	$\lambda=1$	$\lambda=0$
PRESENCE DAYS	1505 days	1554 days
LONGEST GAP	42 days	28 days
TOTAL DEVIATION	1 week	18 weeks

Table 4.3. Results with Persistence

V. CONCLUSIONS AND RECOMMENDATIONS

This thesis develops a computerized system, known as the Pacific Fleet Aircraft Carrier Scheduler (PACACS), to aid in the scheduling of PACFLT aircraft carrier deployments. The system is based on the Carrier Deployment Scheduling (CDS) problem. Instead of using the set covering approach, the CDS problem is formulated as a shortest path problem with side constraints. When a feasible solution exists, the problem can be solved as a linear program and still yield an integer solution.

To validate its effectiveness and illustrate its speed, the PACACS system was used to develop a five year deployment plan using inputs provided by the CINCPACFLT Operations Department. The system produced a weekly deployment schedule in less than 33 CPU seconds on a 60 MHz Pentium personal computer. When compared to the deployment plan produced by the CINCPACFLT scheduling officer, the one generated by PACACS has the following advantages:

1. PACACS' deployment schedule provides more coverage to the AORs. In particular, PACACS' increases the coverage of the Persian Gulf by 49 days.

2. PACACS' deployment schedule has shorter gaps. PACACS decreases the length of time during which there is no carrier coverage of the gulf by 14 days.

3. PACACS provides a schedule in less than 33 seconds after entering the required information. The manual approach requires 7 days to produce a schedule.

4. A feature in PACACS allows it to generate schedules that minimizes changes to the already published schedule. Changes to the published schedule are often disruptive and may induce frustration with and distrust of the scheduling process.

In addition, this thesis also identifies the following areas for future research:

1) Integrate the scheduling of both Atlantic and Pacific Fleets. Often, there is an insufficient number of carriers in the Pacific Fleet to meet the GNFPP requirements. To alleviate this shortage, carriers from the Atlantic Fleet are assigned to cover the Persian Gulf when possible. Combining the scheduling of carriers in both fleets would lead to a more efficient and effective use for all of the Navy's aircraft carriers.

2) Address other aspects of the GNFPP. This thesis only addresses the aircraft carrier forward presence requirements. However, it would be of interest to address other requirements in the GNFPP as well. These requirements include the number of Tomahawk Land Attack Missiles (TLAM), forward presence of Amphibious Ready Groups (ARG) and composite air wings.

3) Develop an elastic formulation for the CDS problem. If the solution to the CDS problem is infeasible, the output only reports this fact. Incorporating an elastic formulation to the CDS problem can greatly assist the user when determining which input parameters need to be adjusted.

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